Microelectromechanical systems

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A mite less than 1 mm on a MEMS device.

Microelectromechanical systems (MEMS) (also written as *micro-electro-mechanical*, or *MicroElectroMechanical*) is the technology of the very small, and merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micromachines (in Japan), or *Micro Systems Technology - MST* (in Europe). MEMS are separate and distinct from the hypothetical vision of molecular nanotechnology or molecular electronics. MEMS are made up of components between 1 to 100 micrometres in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from 20 micrometres (20 millionths of a metre) to a millimetre. They usually consist of a central unit that processes data, the microprocessor and several components that interact with the outside such as microsensors[1]. At these size scales, the standard constructs of classical physics do not always hold true. Due to MEMS' large surface area to volume ratio, surface effects such as electrostatics and wetting dominate volume effects such as inertia or thermal mass.

The potential of very small machines was appreciated long before the technology existed that could make them—see, for example, Richard Feynman's famous 1959 lecture There's Plenty of Room at the Bottom. MEMS became practical once they could be fabricated using modified semiconductor fabrication technologies, normally used to make electronics. These include molding and plating, wet etching (KOH, TMAH) and dry etching (RIE and DRIE), electro discharge machining (EDM), and other technologies capable of manufacturing very small devices.

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MEMS description

MEMS technology can be implemented using a number of different materials and manufacturing techniques; the choice of which will depend on the device being created and the market sector in which it has to operate.

Materials for MEMS Manufacturing

Silicon

Silicon is the material used to create most integrated circuits used in consumer electronics in the modern world. The economies of scale, ready availability of cheap high-quality materials and ability to incorporate electronic functionality make silicon attractive for a wide variety of MEMS applications. Silicon also has significant advantages engendered through its material properties. In single crystal form, silicon is an almost perfect Hookean material, meaning that when it is flexed there is virtually no hysteresis and hence almost no energy dissipation. As well as making for highly repeatable motion, this also makes silicon very reliable as it suffers very little fatigue and can have service lifetimes in the range of billions to trillions of cycles without breaking. The basic techniques for producing all silicon based MEMS devices are deposition of material layers, patterning of these layers by photolithography and then etching to produce the required shapes.

Polymers

Even though the electronics industry provides an economy of scale for the silicon industry, crystalline silicon is still a complex and relatively expensive material to produce. Polymers on the other hand can be produced in huge volumes, with a great variety of material characteristics. MEMS devices can be made from polymers by processes such as injection moulding, embossing or stereolithography and are especially well suited to microfluidic applications such as disposable blood testing cartridges.

Metals

Metals can also be used to create MEMS elements. While metals do not have some of the advantages displayed by silicon in terms of mechanical properties, when used within their limitations, metals can exhibit very high degrees of reliability.

Metals can be deposited by electroplating, evaporation, and sputtering processes.

Commonly used metals include gold, nickel, aluminium, chromium, titanium, tungsten, platinum, and silver.

MEMS Basic Processes

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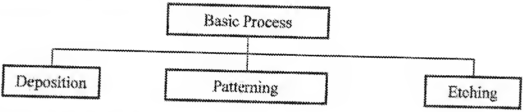

Deposition processes

One of the basic building blocks in MEMS processing is the ability to deposit thin films of material with a thickness anywhere between a few nanometres to about 100 micrometres.

Physical Deposition

There is a type of physical deposition.

Physical Vapor Deposition (PVD)

Sputtering

Evaporation

Chemical Deposition

There are 2 typs of chemical deposition.

Chemical Vapor Deposition

Thermal Oxidation

Patterning

Patterning in MEMS is the transfer of a pattern into a material.

Lithography

Lithography in MEMS context is typically the transfer of a pattern into a photosensitive material by selective exposure to a radiation source such as light. A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If a photosensitive material is selectively exposed to radiation (e.g. by masking some of the radiation) the pattern of the radiation on the material is transferred to the material exposed, as the properties of the exposed and unexposed regions differs.

This exposed region can then be removed or treated providing a mask for the underlying substrate. Photolithography is typically used with metal or other thin film deposition, wet and dry etching.

Photolithography

Electron Beam Lithography

Ion Beam Lithography

X-ray Lithography

Diamond Patterning

Etching processes

There are two basic categories of etching processes: wet and dry etching. In the former, the material is dissolved when immersed in a chemical solution. In the latter, the material is sputtered or dissolved using reactive ions or a vapor phase etchant. See Williams and Muller[2] or Kovacs, Maluf and Peterson[3] for a somewhat dated overview of MEMS etching technologies.

Wet etching

Wet chemical etching consists in a selective removal of material by dipping a substrate into a solution that can dissolve it. Due to the chemical nature of this etching process, a good selectivity can often be obtained, which means that the etching rate of the target material is considerably higher than that of the mask material if selected carefully.

Etchant etching

Isotropic etching

Etching progresses at the same speed in all directions. Long and narrow holes in a mask will produce v-shaped grooves in the silicon. The surface of these grooves can be atomically smooth if the etch is carried out correctly, with dimensions and angles being extremely accurate.

Anisotropic etching

Some single crystal materials, such as silicon, will have different etching rates depending on the crystallographic orientation of the substrate. This is known as anisotropic etching and one of the most common examples is the etching of silicon in KOH (potassium hydroxide), where Si <111> planes etch approximately 100 times slower than other planes (crystallographic orientations). Therefore, etching a rectangular hole in a (100)-Si wafer will result in a pyramid shaped etch pit with 54.7° walls, instead of a hole with curved sidewalls as it would be the case for isotropic etching

Electrochemical etching

Electrochemical etching (ECE) for dopant-selective removal of silicon is a common method to automate and to selectively control etching. An active p-n diode junction is required, and either type of dopant can be the etch-resistant ("etch-stop") material. Boron is the most common etch-stop dopant. In combination with wet anisotropic etching as described above, ECE has been used successfully for controlling silicon diaphragm thickness in commercial piezoresistive silicon pressure sensors. Selectively doped regions can be created either by implantation, diffusion, or epitaxial deposition of silicon.

Dry Etching

Vapor Etching

Xenon difluoride etching

Xenon difluoride (XeF_2) is a dry vapor phase isotropic etch for silicon originally applied for MEMS in 1995 at University of California, Los Angeles[4][5]. Primarily used for releasing metal and dielectric structures by undercutting silicon, XeF_2 has the advantage of a stiction-free release unlike wet etchants. Its etch selectivity to silicon is very high, allowing it to work with photoresist, SiO_2, silicon nitride, and various metals for masking. Its reaction to silicon is "plasmaless", is purely chemical and spontaneous and is often operated in pulsed mode. Models of the etching action are available[6], and university laboratories and various commercial tools offer solutions using this approach.

HF Etching

Hydrogen fluoride is a chemical compound with the formula HF used for etching

Plasma Etching

Sputtering

Reactive ion etching (RIE)

In reactive ion etching (RIE), the substrate is placed inside a reactor in which several gases are introduced. A plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and react with, the surface of the material being etched, forming another gaseous material. This is known as the chemical part of reactive ion etching. There is also a physical part which is similar in nature to the sputtering deposition process. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. It is a very complex task to develop dry etch processes that balance chemical and physical etching, since there are many parameters to adjust. By changing the balance it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical. RIE can be deep and its name will be Deep RIE or DRIE Deep reactive ion etching (DRIE)

A special subclass of RIE which continues to grow rapidly in popularity is deep RIE (DRIE). In this process, etch depths of hundreds of micrometres can be achieved with almost vertical sidewalls. The primary technology is based on the so-called "Bosch process"[7], named after the German company Robert Bosch which filed the original patent, where two different gas compositions are alternated in the reactor. Currently there are two variations of the DRIE. The first variation consists of three distinct steps (the Bosch Process as used in the UNAXIS tool) while the second variation only

consists of two steps (ASE used in the STS tool). In the 1st Variation, the etch cycle is as follows: (i) SF_6 isotropic etch; (ii) C_4F_8 passivation; (iii) SF_6 anisoptropic etch for floor cleaning. In the 2nd variation, steps (i) and (iii) are combined.

Both variations operate similarly. The C_4F_8 creates a polymer on the surface of the substrate, and the second gas composition (SF_6 and O_2) etches the substrate. The polymer is immediately sputtered away by the physical part of the etching, but only on the horizontal surfaces and not the sidewalls. Since the polymer only dissolves very slowly in the chemical part of the etching, it builds up on the sidewalls and protects them from etching. As a result, etching aspect ratios of 50 to 1 can be achieved. The process can easily be used to etch completely through a silicon substrate, and etch rates are 3-6 times higher than wet etching.

MEMS Manufacturing Technologies

Bulk micromachining

Bulk micromachining is the oldest paradigm of silicon based MEMS. The whole thickness of a silicon wafer is used for building the micro-mechanical structures.[3] Silicon is machined using various etching processes. Anodic bonding of glass plates or additional silicon wafers is used for adding features in the third dimension and for hermetic encapsulation. Bulk micromachining has been essential in enabling high performance pressure sensors and accelerometers that have changed the shape of the sensor industry in the 80's and 90's.

Surface micromachining

Surface micromachining uses layers deposited on the surface of a substrate as the structural materials, rather than using the substrate itself.[8] Surface micromachining was created in the late 1980s to render micromachining of silicon more compatible with planar integrated circuit technology, with the goal of combining MEMS and integrated circuits on the same silicon wafer. The original surface micromachining concept was based on thin polycrystalline silicon layers patterned as movable mechanical structures and released by sacrificial etching of the underlying oxide layer. Interdigital comb electrodes were used to produce in-plane forces and to detect in-plane movement capacitively. This MEMS paradigm has enabled the manufacturing of low cost accelerometers for e.g. automotive air-bag systems and other applications where low performance and/or high g-ranges are sufficient. Analog Devices have pioneered the industrialization of surface micromachining and have realized the co-integration of MEMS and integrated circuits.

High aspect ratio (HAR) silicon micromachining

Both bulk and surface silicon micromachining are used in the industrial production of sensors, ink-jet nozzles, and other devices. But in many cases the distinction between these two has diminished. A new etching technology, deep reactive ion etching, has made it possible to combine good performance typical of bulk micromachining with comb structures and in-plane operation typical of surface micromachining. While it is common in surface micromachining to have structural layer thickness in the range of 2 µm, in HAR silicon micromachining the thickness can be from 10 to 100 µm. The materials commonly used in HAR silicon micromachining are thick polycrystalline silicon, known as epi-poly, and bonded silicon-on-insulator (SOI) wafers although processes for bulk silicon wafer also have been created (SCREAM). Bonding a second wafer by glass frit bonding, anodic bonding or alloy bonding is used to protect the MEMS structures. Integrated circuits are typically not combined with HAR silicon micromachining. The consensus of the industry at the moment seems to be that the flexibility and reduced process complexity obtained by having the two functions separated far outweighs the small penalty in packaging. A comparison of different high

aspect-ratio microstructure technologies can be found in the HARMST article.

Applications

In one viewpoint MEMS application is categorized by type of use.

Sensor

Actuator

Structure

In another view point mems applications are categorized by the field of application(Commercial applications include):

- Inkjet printers, which use piezoelectrics or thermal bubble ejection to deposit ink on paper.
- Accelerometers in modern cars for a large number of purposes including airbag deployment in collisions.
- Accelerometers in consumer electronics devices such as game controllers (Nintendo Wii), personal media players / cell phones (Apple iPhone)[9] and a number of Digital Cameras (various Canon Digital IXUS models). Also used in PCs to park the hard disk head when free-fall is detected, to prevent damage and data loss.
- MEMS gyroscopes used in modern cars and other applications to detect yaw; e.g. to deploy a roll over bar or trigger dynamic stability control.
- Silicon pressure sensors e.g. car tire pressure sensors, and disposable blood pressure sensors.
- Displays e.g. the DMD chip in a projector based on DLP technology has on its surface several hundred thousand micromirrors.
- Optical switching technology which is used for switching technology and alignment for data communications.
- Bio-MEMS applications in medical and health related technologies from Lab-On-Chip to MicroTotalAnalysis (biosensor, chemosensor).
- Interferometric modulator display (IMOD) applications in consumer electronics (primarily displays for mobile devices). Used to create interferometric modulation - reflective display technology as found in mirasol displays.

Companies with strong MEMS programs come in many sizes. The larger firms specialize in manufacturing high volume inexpensive components or packaged solutions for end markets such as automobiles, biomedical, and electronics. The successful small firms provide value in innovative solutions and absorb the expense of custom fabrication with high sales margins. In addition, both large and small companies work in R&D to explore MEMS technology.

Research and development

Researchers in MEMS use various engineering software tools to take a design from concept to simulation, prototyping and testing. Finite element analysis is often used in MEMS design. Simulation of dynamics, heat, and electrical domains, among others, can be performed by ANSYS, COMSOL and CoventorWare-ANALZYER. Other software, such as CoventorWare-ARCHITECT and MEMS-PRO, is used to produce a design layout suitable for delivery to a fabrication firm and even simulate the MEMS embedded in a system. Once prototypes are on-hand, researchers can test the specimens using various instruments, including laser doppler scanning vibrometers, microscopes, and stroboscopes.

Industry structure

The global market for micro-electromechanical systems, which includes products such as automobile airbag systems, display systems and inkjet cartridges totaled $40 billion in 2006 according to Global MEMS/Microsystems Markets and Opportunities, a comprehensive new market research report from SEMI and Yole Developpement.[1] A 2009 report from The Information Network [http:/www.theinformationnet.com] points out that the market in 2008 was $6.9 billion.

MEMS devices are defined as die-level components of first-level packaging, and include pressure sensors, accelerometers, gyroscopes, microphones, digital mirror displays, micro fluidic devices, etc. The materials and equipment used to manufacture MEMS devices topped $1 billion worldwide in 2006. Materials demand is driven by substrates, making up over 70 per cent of the market, packaging coatings and increasing use of chemical mechanical planarization (CMP). While MEMS manufacturing continues to be dominated by used semiconductor equipment, there is a migration to 200mm lines and select new tools, including etch and bonding for certain MEMS applications.

See also

- Nanoelectromechanical systems are similar to MEMS but smaller
- MOEMS, Micro Opto-Electrical-Mechanical Systems, MEMS including optical elements
- Micropower Hydrogen generators, gas turbines, and electrical generators made of etched silicon
- IBM Millipede, a MEMS technology for non-volatile data storage of more than a terabit per square inch
- Lucent who developed highly advanced optical telecommunications switches
- Cantilever one of the most common forms of MEMS.
- MEMS Thermal Actuator MEMS actuation created by thermal expansion
- Scratch Drive Actuator MEMS actuation using repeatedly applied voltage differences
- Electrostatic motors used where coils are difficult to fabricate
- Alcatel Micro Machining Systems Manufacturers of DRIE systems
- Infineon Technologies direct TPMS sensors
- Robert Bosch GmbH Producing more than 200 million MEMS in pressure, angular rate, acceleration per year in their plant in Reutlingen (and are currently building nearby another plant with an output of over 1 million chips per day), first company with more than 1 billion MEMS sensors produced
- Sensirion Leading manufacturer of MEMS flow sensors
- Qualcomm Qualcomm MEMS Technologies - MEMS-based display technology for mobile devices
- Finetech, Equipment manufacturer for MEMS assembly
- VTI Technologies, designer and manufacturer of silicon capacitive acceleration and pressure sensors.
- IMTEK, Germany' largest MEMS research institute.
- Brain-computer interface
- MEMS sensor generations.
- Kelvin probe force microscope

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External links

- Amkor Technology MEMS Packaging Technology Solutions.
- *A MEMS STEAM TURBINE POWER PLANT-ON-A-CHIP*, L. G. Fréchette, C. Lee, S. Arslan, Y-C. Liu, Proc. PowerMEMS'03, Makuhari, Japan, 4-5 December 2003.
- The Outer Limits, Mind Reacher
- *Videos on MEMS and their applications*.

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